

# **A Method for Assessing the Life-Cycle Costs of Diesel and Electric Buses**

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# ABSTRACT

World-wide concern about the future supply and price of petroleum fuel has heightened interest in alternative forms of energy. Urban transit is an area where electrical energy may be substituted for petroleum fuel. This report presents a method of analysing various electrical and electric hybrid bus systems taking into account the influence of bus headway and comparing their costs with those of the regular diesel bus. The method also incorporates the concepts of Value Analysis which puts in perspective the additional costs that may be associated with the use of particular forms of energy.

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## 1/ INTRODUCTION

In recent years, the world has experienced two periods of oil shortage which have resulted in sudden increases in the cost of oil. As the supply of oil declines there is an increasing interest in developing alternative and, where possible, indigenous energy sources. Also, as the price of oil rises, alternative energy sources become increasingly cost-competitive. Decisions to move from oil toward alternative energy sources become more attractive, and may be made for various reasons, including cost, quantity and assurance of supply, desire to use indigenous sources, industrial development opportunities, and employment. Hence it is clear that cost, although important, is not the sole, or in some cases even the most important criterion on which such decisions are based. At the same time, it is essential that the relative costs of using alternative energy sources be compared on a sound and equitable basis so that they may be considered properly in such decision-making.

This report develops a method for assessing the relative life-cycle costs of diesel buses and electric and electric-hybrid buses. The report is concerned with the technique of cost comparison rather than with drawing conclusions based on such comparisons, although such conclusions may appear implicit in the examples used. The interest here is in developing methodology that various investigators and decision-makers can apply, using the data appropriate to their own situation at the time of study. Conditions and relative costs will change with time, but the method of comparison will remain valid. The method is based on a life-cycle cost analysis, together with the concepts of value analysis.

For definition of terms, the reader is directed to the Glossary, page 27.

## 2/ BASIS FOR COST COMPARISON

Before one can make any comparison of costs, it is essential to ensure that these costs are arrived at from the same basis. This means the costs are available in the same currency, at the same point in time, and preferably on the same property. It is also important that cost differences for similar items be consistent with experience. The costs developed and used in making comparisons in this report are life-cycle costs based on the distance travelled by the buses. These include all cost elements incurred in moving the buses. The comparison could also be carried out on a basis of present worth without changing the end result. However, it is easier to relate these costs to typical industry data and to fuel consumption if the distance travelled by the bus is used as the basis.

The costing data presented in this report have been used primarily for the purpose of illustrating the method of comparison. The diesel and trolley bus costs, however, are based on factual data, but do not include the substation land costs. The costs on the pure battery and battery hybrids, however, are somewhat speculative due to the shortage of data. In the case of the diesel hybrids, the normalized life-cycle costs were obtained from Reference 1.

### 2.1/ Life-Cycle Costs

The main purpose of establishing life-cycle costs is to combine the initial capital expenditures with the ongoing costs of operating the bus system. In the case of a bus system, however, the cost components can be divided into two main categories. These are time-related costs, which include capital and other annual costs, and distance-related costs, such as drivers, maintenance, and fuel or energy.

#### 2.1.1/ Time-Related Costs

Accounting for the capital costs appears simple. Standard equations or mortgage tables will quickly provide factors which convert capital costs into annual payments. Problems arise, however, with choice of inflation

rates, interest rates, and the life of the system. The twin problems of inflation and interest rate have been accommodated by using constant value dollars as of 1980 and an effective or differential interest rate (discount rate) of 4%. The life of the system components may vary and this is dealt with in the analysis.

The standard annual payment equation used in this report is given below:

$$C_y = \frac{a}{p} = \frac{i(1+i)^y}{(1+i)^y - 1}$$

where:

- a = annual payment
- p = principal amount borrowed
- y = period of repayment in years
- i = annual interest rate

If the system contains annual costs which do not relate to bus distance travelled, such as substation maintenance, this is added to the annualized capital cost. The total annual time-related costs are then divided by the annual distance travelled by the fleet to obtain the total annual time-related cost on a distance basis.

#### 2.1.2/ Distance-Related Costs

The distance-related costs are those generally accepted as being closely tied to the movement of the bus. Fuel and energy costs and maintenance are clearly related to distance travelled and are segregated as such. The driver costs, however, which are strictly speaking time-dependent, are related to distance by means of the schedule speed. In this report it is assumed that the trolley bus will achieve the same schedule speed as the diesel bus. This is not necessarily correct, as restrictions on mobility caused by the trolley wires may slow down the trolley bus. Where battery buses require a significant time to change batteries, they will suffer from lower schedule speeds, but this has not been taken into account in this report.

### 2.1.3/ Combined Costs

When the time- and distance-related costs have been developed, they can be added to give a life-cycle cost on the basis of the distance travelled by the bus. The data thus obtained permits comparison with similar data produced by the industry. They can also be related easily to fuel and energy consumption data which are usually available on a distance basis.

### 2.1.4/ Bus Headway

In the case of diesel buses, the wayside equipment is minimal and the cost of the storage and maintenance facilities can be evaluated by sharing the cost over the number of buses. This assumes that these capital costs are proportional to the number of buses.

The trolley bus, however, requires expensive wayside equipment. The capital cost of this equipment must be shared by the buses on the route. Theoretically, the required power capacity of the power supply equipment is proportional to the number of buses using the system. However, the cost is not proportional to the capacity, and it is also usual to install a power supply system which is capable of providing the ultimate required capacity. This means that the capital cost of the power supply system is largely independent of the number of buses on the system.

It is essential to recognize that the presence of more buses on a trolley bus system will tend to reduce the life-cycle cost per bus-kilometre. The analysis takes the bus density into account by using the bus headway to derive simple equations for a life-cycle cost.

### 3/ THE DIESEL BUS SYSTEM

#### 3.1/ Description of Facilities

The diesel bus system represents the most basic system, with minimal wayside equipment. The bus itself is a standard piece of equipment 12.3 m long with a GVW of 13 t. The wayside facilities are simply those required for storage, maintenance, refueling and cleaning. The capital costs of these wayside facilities form a small proportion of the total life-cycle costs, and differ only slightly in cost between systems. They are therefore included in the analysis as a lump sum, per bus.

The diesel bus is assumed to last for 15 years and the capital cost recovery factor reflects this. The storage and maintenance facilities, on the other hand, are assumed to last for 30 years. An effective interest rate is taken at 4% in constant dollars (i.e., inflation is excluded). A cost factor of 1.2 has been used in estimating the cost of structures to cover 15% for contingency and 5% for engineering.

#### 3.2/ Diesel Bus Life-Cycle Cost

The various expressions for the different cost elements are developed in this section in general terms. Typical values are then substituted to derive representative values.

All the annualized capital costs of the bus are converted into cost per bus-kilometre and added to the operational costs which already exist on this basis. Thus:

- Annualized capital cost of one diesel bus
$$= C_{15}(B_d + P_d) (\$/\text{yr})/\text{bus} \quad (1)$$

- Annualized capital cost of maintenance and storage facility
$$= 1.2 C_{30} M_d (\$/\text{yr})/\text{bus} \quad (2)$$

- Total annualized capital cost
$$= C_{15}(B_d + P_d) + 1.2 C_{30} M_d (\$/\text{yr})/\text{bus} \quad (3)$$

The total annualized cost may be converted to a bus-kilometre basis by dividing by D, the annual distance travelled by the average bus in the fleet over its lifetime.

It is now possible to add the energy, maintenance, and other operating costs to obtain the life-cycle cost.

- Total life-cycle cost
 
$$= O_d + I_d + T_d + [C_{15}(B_d + P_d) + 1.2 C_{30} M_d] / D \text{ (\$/km)/bus} \quad (4)$$

This expression is simplified for the purpose of making comparisons by substituting typical cost data obtained in Ontario in 1980 dollars.

- Total diesel bus capital cost  $B_d + P_d = 110\,000 \text{ \$}/\text{bus}$
- Capital cost of maintenance and storage facility  $M_d = 22\,000 \text{ \$}/\text{bus}$
- Operational cost of bus excluding maintenance and energy  $O_d = 0.91 \text{ (\$/km)/bus}$
- Cost of maintenance and service  $I_d = 0.25 \text{ (\$/km)/bus}$
- Cost of fuel or energy  $T_d = 0.125 \text{ (\$/km)/bus}$
- Annual distance travelled  $D = 64\,400 \text{ km}/\text{yr}/\text{bus}$

- Capital cost factor  $C_{15} = \frac{0.04(1.04)^{15}}{(1.04)^{15} - 1} = 0.09$

$$C_{30} = \frac{0.04(1.04)^{30}}{(1.04)^{30} - 1} = 0.058$$

When these numbers are substituted in Equation 4, the following cost is obtained.

- Diesel bus-life cycle cost  $= 1.463 \text{ (\$/km)/bus}$

This basic cost will be used to normalize all other costs developed for other systems. In these terms, therefore, the diesel bus life-cycle cost will break down as follows:

- Life-cycle cost  $= 1.0$
- Apparent energy component  $= 0.085 = (0.125 \div 1.463)$
- Remaining life-cycle cost  $= 0.915$

#### 4/ THE TROLLEY BUS SYSTEM

##### 4.1/ Description of Facilities

###### 4.1.1/ Electric Supply System

###### Substations

The purpose of substations is to convert the high-voltage alternating current provided by the electrical utility into low-voltage direct current used by the trolley buses. The power handling capacity of a given system is usually chosen to provide for the future ultimate requirements. This is usually regarded as more economical than increasing the capacity as more buses are added to the system.

The capacity and spacing of these substations depend largely on economic analysis. Large-capacity stations can be placed further apart with the provision of heavy and expensive feeder cables to reinforce the current carrying capacity of the contact wire. However, with the modern tendency to have all heavy feeder cables placed underground in costly ducts, and the fact that modern stations can be unmanned and automatic, the economics now tend to favour low-capacity substations with close spacings. The difference in cost, however, is not significant and well within the accuracy of the estimates used in this study. Land costs associated with those substations have been neglected.

###### Overhead Contact Wires

The overhead wires are used to distribute the electric current to the moving vehicles. Each vehicle must be connected to a supply and a return wire. Thus, a pair of wires are strung at about 5 to 6 m above the road surface. These wires are approximately 12 mm in diameter and slightly grooved to permit clamping from above without interference with the smooth motion of the trolley poles on the vehicle. The clamps holding the wire are then attached to the suspension wires which traverse the street. These suspension wires may be attached to their own poles, existing poles, or a convenient building. The overhead suspension arrangements in the area of intersecting routes and branching lines become very complex and add to the cost of the trolley wire system. The cost of the overhead wire system is therefore dependent on the

actual route, the number of intersections, branching lines and the available suspension points. Further cost variations may be introduced by the choice of a simple so-called hard suspension system and the alternative complex or soft suspension system. The latter is said to lead to lower maintenance and breakdown costs.

#### 4.1.2/ The Trolley Bus

The trolley bus body was originally designed specifically for the trolley bus. These were also the buses which were responsible for the enviable reputation for longevity of the trolley bus. However, present day production economics make it essential to use the same bus body as the diesel bus to produce a GVW of 15 t. The life of the bus body may now be about 15 years for both diesel and trolley bus.

The electric propulsion system of the trolley bus however, with refurbishing at 15 years, is expected to last about 30 years. This of course assumes that new improved propulsion systems will not displace the current systems until they show some definite life-cycle cost advantages to justify premature scrapping of existing equipment.

The current propulsion systems consist of a direct current (d.c.) motor supplied from either a resistance controller or a solid-state chopper controller. The chopper usually permits recovery of much of the vehicle kinetic energy when braking, and this reduces the vehicle energy consumption by about 25%. The chopper, however, is usually larger, heavier and more costly than the resistance controller. New systems using alternating current (a.c.) induction motors and inverter controllers are being promoted. However, reliable cost and benefit data on their performance are difficult to find. In this report, a d.c. chopper system has been assumed in the bus costing. The energy consumption data used reflect the regenerative energy savings made possible by the chopper.

#### 4.1.3/ Maintenance and Storage Facilities

The maintenance and storage facilities for the trolley bus tend to cost slightly more than for the diesel bus. This is because of the complex system of overhead wiring that is required in the storage area. This

extra cost could be eliminated if trolley buses are provided with off-wire capability. The trolley buses, however, would cost more to purchase and operate, and the net benefits may be uncertain. This option is considered under Trolley/Battery Buses in Appendix B.

#### 4.2/ Trolley Bus Life-Cycle Cost

As in the case of the diesel bus, the life-cycle costs are developed in general terms, then typical cost elements are substituted to arrive at typical life-cycle costs to facilitate the comparison.

o The annualized capital cost of one trolley bus

$$= C_{15}B_t + C_{30}P_t \text{ ($/yr)/bus} \quad (5)$$

The bus body is assumed to have a life of 15 years and the propulsion system 30 years.

o The annualized capital cost of maintenance and storage facilities

$$= 1.2 C_{30}M_t \text{ ($/yr)/bus} \quad (6)$$

o The annualized capital cost of power distribution system

$$= 1.2 C_{30}W_t \text{ ($/yr)/route-km} \quad (7)$$

To obtain the total annualized capital cost per route-kilometre, Equations 5 and 6 are multiplied by N, the number of buses per route-kilometre, and added to Equation 7. Thus:

o Total annualized capital cost per route-kilometre

$$= N(C_{15}B_t + C_{30}P_t + 1.2 C_{30}M_t) + 1.2 C_{30}W_t \text{ ($/yr)/route-km} \quad (8)$$

The annual maintenance cost of the overhead and power distribution system  $K_t$  can be added to Equation 8 to give the total annualized route-related cost on a route-kilometre basis.

o Total annualized route-related costs

$$= N(C_{15}B_t + C_{30}P_t + 1.2 C_{30}M_t) + 1.2 C_{30}W_t + K_t \text{ ($/yr)/route-km} \quad (9)$$

The total annual distance travelled by all the buses per route-kilometre is given by the product ND.

Therefore, the total life-cycle costs per bus-kilometre can be obtained by dividing Equation 9 by ND and adding the costs usually related to the distance travelled by the bus. Thus:

- Total life-cycle cost
 
$$= O_t + T_t + I_t + (C_{15}B_t + C_{30}P_t + 1.2 C_{30}M_t)/D + (1.2C_{30}W_t + K_t)/ND \text{ (\$/km)/bus} \quad (10)$$

It is generally more useful to express N, the number of buses per kilometre, in terms of the headway and schedule speed S. Thus:

- $N = 2 \times 60 \times 1.1/hS = 132/hS \text{ buses/km} \quad (11)$

where allowance is made for two-way flow and 10% of the buses are held in reserve, and h is headway in minutes, and S is schedule speed.

By substituting for N in Equation 10, the following equation is obtained:

- Total life-cycle cost
 
$$= O_t + T_t + I_t + (C_{15}B_t + C_{30}P_t + 1.2 C_{30}M_t)/D + hS(1.2C_{30}W_t + K_t)/132D \text{ (\$/km)/bus} \quad (12)$$

In order to simplify the equations and permit comparison between different systems, typical cost data have been obtained and substituted for the symbols. These data have been obtained from Ontario sources and are used here primarily to illustrate the method of analysis.

The following data include typical cost estimates in mid-1980 dollars. The bus propulsion system is chopper-controlled which permits partial recovery of the bus kinetic energy. The energy saving is allowed for in the energy consumption figures.

- Capital cost of bus body  $B_t = 100\,000 \text{ \$/bus}$
- Capital cost of bus propulsion system  $P_t = 80\,000 \text{ \$/bus}$
- Capital cost of maintenance and storage  $M_t = 24\,000 \text{ \$/bus}$
- Capital cost of wayside equipment  $W_t = 320\,000 \text{ \$/route-km}$

- Annual cost of maintaining wayside system  $K_t = 7000 \text{ (\$/yr)/route km}$
- Operational cost of bus excluding maintenance and energy  $O_t = 0.93 \text{ (route-km)/bus}$
- Cost of fuel or energy  $T_t = 0.076 \text{ (\$/km)/bus}$
- Cost of maintenance and service  $I_t = 0.35 \text{ (\$/km)/bus}$
- Bus schedule speed  $S = 20.0 \text{ km/h}$
- Cost of electrical energy  $J = 0.038 \text{ \$/kWh}$
- Electrical energy used per km  $E_t = 2.0 \text{ (kWh/km)/bus}$
- Annual distance travelled by bus  $D = 64\,000 \text{ km/yr}$

When these values are substituted in the equation, and  $C_{15}$  and  $C_{30}$  are given the same values as in the diesel bus case, the equation simplifies to the following:

- Trolley bus life-cycle cost  $= 1.59 + 0.069h \text{ (\$/km)/bus}$  (13)

For the purpose of comparison, it is necessary to normalize Equation 13 in terms of the diesel bus life cycle cost of 1.463 (\\$/km)/bus obtained in Section 3.

- Normalized trolley bus life-cycle cost  $= (1.59 + 0.069h)/1.463$   
 $= 1.087 + 0.047h$  (14)

For headways of 4 min and 10 min this normalized cost becomes:

- for  $h = 4$ , Equation 14 becomes  $1.087 + 0.047 \times 4 = 1.278$
- for  $h = 10$ , Equation 14 becomes  $1.087 + 0.047 \times 10 = 1.56$

The energy element  $T_t$  of the trolley bus life-cycle cost on the normalized basis becomes:

$$T_t = 0.076 \div 1.463 = 0.052$$

Analyses for the battery bus and the trolley/battery hybrid bus, similar to those in Sections 3 and 4, are shown in Appendices A and B.

## 5/ COMPARING COSTS

Having established the life-cycle cost of the various alternatives, it now becomes necessary to compare them on a rational basis. This task is made easier by borrowing ideas from the techniques developed in value analysis. Value analysis was first developed as a systematic aid in making rational value decisions in the field of machine design [2].

### 5.1/ The Value Analysis Approach

The basis of the value analysis technique is the concept of value which is defined as:

$$\text{Value} = \frac{\text{Function}}{\text{Cost}}$$

A simple example may help to explain application of this technique. Suppose the function is defined as "the temporary attachment of two pieces of cloth." This may be achieved by means of a safety pin, button, velcro tape, or zipper. When these are costed and compared it will be found that the safety pin probably represents the highest value (i.e., achievement of the function at minimum cost). Further examination will show, however, that the other devices possess additional beneficial functions such as convenience and continuous, rather than point, attachments. These additional functions may also be evaluated in a similar manner. The extra cost of the button, for example, over the safety pin can be attributed to the function of convenience or appearance and evaluated accordingly. The safety pin, therefore, represents minimum cost for the main function against which all others must be compared. Any function may be similarly examined by separating and evaluating the various components of its function.

A similar approach may be used in the case of public transportation. In this case the main function is providing transportation and the cost is the life-cycle cost of doing so.

The function of providing transportation is made up of many elements which will be identical regardless of the energy source or motive power

used. Here, it is useful to focus attention on the energy component. That is, maximum value will be achieved when the transportation function is provided at minimum energy cost. If another, more costly energy source is used, and the transportation function that is provided remains unchanged, the value decreases because of the increased costs associated with this energy source.

By separating the energy cost in this manner, it is then possible to examine and compare the effective cost of energy for the various systems.

## 5.2/ Effective Energy Cost

The main objective in utilizing electrical energy is to avoid using fuel oil. The function performed by each is to provide propulsion. The intrinsic value of performing that function is the least cost means of providing it. It is therefore necessary to divide the life-cycle cost into two components (one of which is energy) to provide propulsion. The life-cycle costs and the energy costs developed in Sections 3 and 4 and Appendices A and B are tabulated in Columns 1 and 2 of Table 1.

Columns 3 and 4 of this table are a repeat of Columns 1 and 2 but normalized relative to 1.463 (\$/km)/bus, the life-cycle cost of the diesel bus, which is given a value of 1.0.

Column 5 is the life-cycle cost of the diesel bus minus its apparent energy cost. This figure is 0.915 and represents the intrinsic value of providing the moving buses when energy cost is neglected. All other bus systems provide essentially the same function and can only be assigned the same intrinsic value of 0.915.

Column 6 shows the extra life-cycle cost of using each of the bus systems and this is obtained by subtracting Column 5 from 3. The Column 6 figures, therefore, indicate the effective cost of energy for each system. The normalized values of Column 3 are shown graphically in Figure 1 where they are subdivided into the two components, Maximum Intrinsic Value of U, Column 5, and Effective Energy Cost, Column 6. Column 7 is simply a repeat of Column 6, but normalized on the basis of the cost of the fuel used by the diesel bus.

Column 8 is a repeat of Column 7 with the taxation element of fuel cost removed. If government subsidies are to be made available to operate vehicles using an alternative energy source, the funds will come from taxation revenue. The diesel fuel tax is a source of revenue of approximately 50% of the fuel cost. Thus, the net cost to society must take into account the tax revenue lost due to the energy substitution. Looked at another way, all energy sources should be looked at on the same basis -- either all without tax, or all with tax -- because, presumably, with the displacement of petroleum fuels and loss of tax revenue, the alternative fuels or energy sources would have to be taxed to recover such revenue. Column 7, therefore, reflects the energy cost relationships as seen by the bus operators. Columns 8 and 9 reflect the energy cost relationships as seen by governments involved in subsidies for electric transportation.

These columns are, in effect, a value analysis list of the alternative energy costs based on the energy cost of the diesel which has been assigned the value of unity. Higher ratios are obtained using the pre-tax cost of fuel as a base. It should be noted that all the extra costs required by these systems become necessary only when electrical energy is selected and should be regarded as contributing to the energy costs. The effective energy cost includes these extra costs and portrays an assessment of relative energy costs.

In essence, the concept of assigning the cost of the capital equipment required to use electrical energy to the cost of the energy is not new. When electrical energy is purchased, the cost of the capital equipment required to produce and distribute it comprises up to 70% of the cost of the energy. The above method is applying the same logic to the consuming end of the electrical energy cycle.

## 6/ CONCLUSION

The application of Value Analysis techniques to the comparison of energy cost provides a new way of examining the effective cost of electrical energy. These techniques may also apply to other situations where alternative forms of energy are being investigated.

The ratios shown in Table 1, Column 8, are illustrative and will, of course, be highly sensitive to any change in the capital costs of the electrical systems and battery replacement costs. Also, the rising cost of diesel fuel would reduce these ratios. This means that each case must be examined taking into account the capital costs of a given proposed system, its site conditions, and the energy costs at a given point in time when the system is to be implemented.

The analytical framework and methodology presented here will facilitate the comparison of systems by allowing planners to substitute their own cost data into the equations.

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TABLE 1/ Bus Types and Costs

| BUS TYPE               | Costs              |                       |                            |       |                                       |                |                                                                             |                                  |                                             |
|------------------------|--------------------|-----------------------|----------------------------|-------|---------------------------------------|----------------|-----------------------------------------------------------------------------|----------------------------------|---------------------------------------------|
|                        | LCC<br>(\$/km)/bus | ENERGY<br>(\$/km)/bus | LCC<br>normalized on 1.463 | AEC   | Maximum<br>Intrinsic<br>Value of<br>u | EEE<br>(3)-(5) | EEC<br>Normalized on<br>Diesel Fuel<br>Cost of<br>0.085 (\$)<br>(6) ÷ 0.085 | EEC<br>(7)<br>before<br>Tax (\$) | EEC<br>(8)<br>Normalized<br>on<br>0.67 (\$) |
|                        | (1)                | (2)                   | (3)                        | (4)   | (5)                                   | (6)            | (7)                                                                         | (8)                              | (9)                                         |
| Diesel                 | 1.463              | 0.124                 | 1.0                        | 0.085 | 0.915                                 | 0.085          | 1.0                                                                         | 0.67                             | 1.0                                         |
| Trolley h = 4          | 1.866              | 0.076                 | 1.278                      | 0.052 | 0.915                                 | 0.363          | 4.27                                                                        | 4.27                             | 6.4                                         |
| Trolley h = 10         | 2.28               | 0.076                 | 1.56                       | 0.052 | 0.915                                 | 0.645          | 7.6                                                                         | 7.6                              | 11.38                                       |
| Battery                | 2.49               | 0.167                 | 1.7                        | 0.114 | 0.915                                 | 0.785          | 9.2                                                                         | 9.2                              | 13.8                                        |
| Trolley/Battery h = 4  | 2.17               | 0.106                 | 1.483                      | 0.073 | 0.915                                 | 0.568          | 6.68                                                                        | 6.68                             | 10.2                                        |
| Trolley/Battery h = 10 | 2.49               | 0.106                 | 1.705                      | 0.073 | 0.915                                 | 0.79           | 9.29                                                                        | 9.29                             | 13.94                                       |
| Trolley/Diesel h = ?   |                    |                       | 1.2*                       |       | 0.915                                 | 0.285          | 3.35                                                                        |                                  |                                             |
| Battery/Diesel         |                    |                       | 1.28*                      |       | 0.915                                 | 0.365          | 4.29                                                                        |                                  |                                             |

Column (7) is Column 6 normalized on diesel fuel after-tax cost of 0.085

Column (8) is Column 7 without the tax on fuel

Column (9) is Column 8 normalized as 0.67

LCC is Total Life Cycle cost  
AEC is Apparent Energy Cost  
U is 0.915, Diesel Bus (LCC - AEC)  
EEC is Effective Energy Cost  
h is bus headway in minutes  
\* LCC drawn from Reference 1 headway (H) was not given

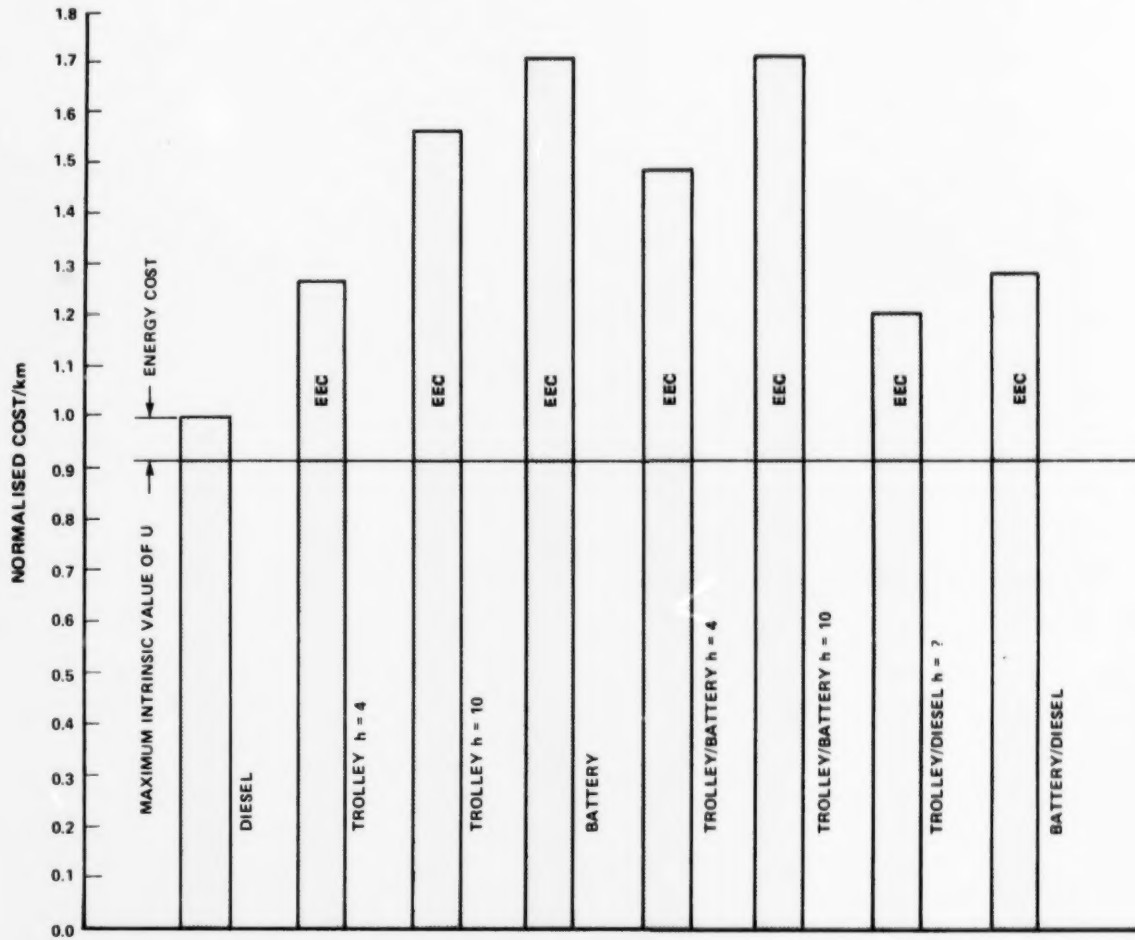


Figure 1/ Normalised LCC

## APPENDIX A

### A.1/ The Battery Bus System

The battery bus propulsion system is essentially the same as the trolley bus. The main difference is that the trolley bus requires two trolley poles and a contact wire system, whereas the battery bus requires a massive electric battery to store its energy, and a means of replacing the energy when it is consumed. The weight of the battery and axle loading limitations may make it necessary to provide a trailer for the purpose of carrying the battery.

Two methods of energy replacement are used. The simplest is to recharge the batteries while on board the bus or trailer. This system prevents the bus from being used while charging. In order to provide a bus availability equal to that of the average diesel bus, three trailer battery units are required per bus (see Gurley, Reference A1). Even so, the time taken to effect a trailer change-over may slightly reduce schedule speed. The more complex system is to exchange the batteries. This has the advantage of allowing the bus to resume service after a 4-min change-over period. The battery exchange, however, involves complex automatic change-over equipment and also requires the extra batteries.

The factors governing the choice of energy replacement system are dependent on the use pattern of the buses, and the choice will usually be determined by a cost analysis of the alternatives for a specific application. Gurley [A1] has indicated that the three-trailer system appears to be the least costly. This system will, therefore, be used to generate typical cost data.

### A.2/ Maintenance, Storage, and Battery Charging Facilities

The maintenance facility will be similar to that used for the trolley bus, except that the overhead trolley contact wires will be replaced by a battery storage and charging facility. Such facilities will require a battery charger with about 30 kW of charging capacity for each bus, and a means of moving the heavy trailers to and from the chargers. Facilities will also be required to remove and replace batteries in the trailers.

### A.3/ Life-Cycle Cost

The life-cycle cost equation is developed in general terms, as in the other systems. The use of batteries, however, introduces several new cost components and factors which affect life-cycle costs. The costs of the three battery trailers are incorporated in the bus body cost. The cost of the set of batteries is included as a separate item and the cost of the battery handling and charging facilities are included in the capital cost of the maintenance and storage facility. The battery charging equipment needs to be maintained and this cost is included as a separate additional cost.

- The annualized cost of one battery bus  

$$= C_{15}B_b + C_{30}P_b \text{ (\$/yr)/bus} \quad (A.1)$$

- The annualized cost of three sets of batteries  

$$= 0.9 C_3 A_b \text{ (\$/yr)/bus} \quad (A.2)$$

It is assumed that the salvage value of the batteries is 10% and that they will last three years.

- The annualized cost of the maintenance and storage facility  

$$= 1.2 C_{30} M_b \text{ (\$/yr)/bus} \quad (A.3)$$

- The annual cost of maintaining the battery-charging equipment  

$$= K_b \text{ (\$/yr)/bus} \quad (A.4)$$

These annual costs can be divided by the average annual distance (D) travelled by the bus and added to the other costs already available on a basis of distance. Thus:

- The life-cycle cost for the battery  

$$= O_b + T_b + I_b + (G_{15}B_b + C_{30}P_b + 0.9 C_3 A_b + 1.2 C_{30}M_b + K_b)/D_b \quad (A.5)$$

In order to illustrate the application of the comparison method, numbers must be substituted in Equation A.5. Unfortunately the battery bus exists only in the form of prototypes, so hard data are not available.

However, the following costs are a fair reflection of those available, converted to mid-1980 Canadian dollars and applied to the standard capacity bus body.

|                                                                  |   |         |              |
|------------------------------------------------------------------|---|---------|--------------|
| $B_b$ (Capital cost of bus body)                                 | = | 130 000 | \$/bus       |
| $P_b$ (Capital cost of bus propulsion system)                    | = | 80 000  | \$/bus       |
| $A_b$ (Capital cost of battery)                                  | = | 124 000 | \$/bus       |
| $M_b$ (Capital cost of maintenance and storage)                  | = | 30 000  | \$/bus       |
| $K_b$ (Annual cost of maintaining wayside system)                | = | 2 000   | \$/bus       |
| $O_b$ (Operational cost of bus excluding maintenance and energy) | = | 0.93    | (\$/km)bus   |
| $T_b$ (Cost of fuel or energy)                                   | = | 0.167   | (\$/km)bus   |
| $I_b$ (Cost of maintenance and service)                          | = | 0.45    | (\$/km)bus   |
| $J$ (Cost of electrical energy)                                  | = | 0.038   | \$/kWh       |
| $E_b$ (Electrical energy used per km)                            | = | 4.4     | (kWh/km)/bus |
| $D$ (Annual distance travelled by bus)                           | = | 64 400  | (km/yr)/bus  |

The capital cost recovery factor for three years is:

$$C_3 = \frac{0.04(1.04)^3}{(1.04)^3 - 1} = 0.36$$

When the above values are substituted in Equation A.5, the battery bus life-cycle cost = 2.49 (\$/km)/bus. As this cost is to be compared with that of the diesel bus, it becomes 1.7 when normalized relative to the diesel bus. The energy component of the life-cycle cost ( $T_b$ ) is 0.167 (\$/km)/bus and becomes 0.114 when normalized to the diesel bus life-cycle cost.

#### A.4/ Appendix A References

- [A1] Gurley, A., "Towards a More Versatile Public Passenger Transport System Based on Experience with the Leyland/Bosch/Chloride Bus at Runcorn, Cheshire," Electric Vehicle Development Group, 2nd International Conference, May 23-24, 1978.

## APPENDIX B

### B.1/ The Trolley/Battery Hybrid Bus System

In this system a battery is carried on board the bus to permit normal operation of the bus while it is disconnected from the contact wire system. This system offers the possibility of extending the electrified routes while avoiding the cost of the contact wire system extension, the visual pollution of the wires, and the lack of operational flexibility associated with the wires. Only the problem of cost will be dealt with here as the other benefits are difficult to evaluate on the basis of cost. Furthermore, this system will be costed as a completely new system rather than an extension in order to fully account for the capital element of the life-cycle costs.

### B.2/ Electrical Supply System

The main advantage of this hybrid system is the possibility of reducing the cost of the contact wire system by using sections of the bus route which have no wires. These parts of the route are known as "off-line", while the wired sections are known as "on-line". It is essential, therefore, to establish the maximum off-line to on-line ratio to gain the greatest benefits. This optimization will not be described here, but it can be shown that a minimum ratio of battery weight to GVW of 14% is required to provide a peak power of 10 kW/t. With this battery fraction and a schedule speed of 20 km/h, the off-line to on-line ratio is 0.6. An increase in the battery mass fraction for the size of bus under discussion provides no increase in this ratio due to the limitations in current available from the trolley pole contact. A reduction of the schedule speed will increase the off-line to on-line ratio; however 20 km/h is the schedule speed used in this comparison.

The use of battery will also permit the elimination of the expensive overhead wiring at complex intersections. This is subject to the satisfactory development of automatic devices to detach and replace the trolley pole on the wire.

The battery will also eliminate the costly contact wire system in the storage and maintenance areas. This reduction in the cost of the contact wire, however, does not apply to the substations. The total energy required will be higher than that of the regular trolley system, because of the extra losses in the battery and battery charger. This means that the number of substations for the "on-wire" system will be more than that needed for an equivalent regular trolley bus system.

### **B.3/ The Trolley/Battery Bus**

This hybrid bus will be similar to the trolley bus with the addition of a low capacity battery and a charger capable of a high rate of charge. The battery will have a low energy density as the high rates of charge used in this application will only permit charging up to 80% of full charge. As the discharge is normally allowed down to 20% charge, the battery capacity is effectively reduced from the normal 80% to 60%. The rate of charge adopted is about 50% per hour, so the charger is both powerful and expensive, and may cost as much as the chopper motor controller.

Because the battery is subject to high rates of charge, it will be necessary to charge the battery weekly at a low rate of charge to equalize the cells and maintain the battery capacity. This will require the provision of battery-charging facilities in the storage area. The storage and maintenance facility will also require battery-handling equipment to remove and replace batteries.

### **B.4/ Life-Cycle Costs**

The components of life-cycle cost can be identified and related in general terms. In order to demonstrate the method, specific values for these component costs have been developed. These buses, however, are in the prototype stage and little detailed information is available on costs. The ratio of the life-cycle costs for the trolley/battery bus relative to the diesel bus given by this method is, however, reasonably close to published data.

- The annualized capital cost of one trolley battery bus  

$$= C_{15}B_C + C_{30}P_t \text{ ($/yr)/bus} \quad (B.1)$$

- The annualized capital cost of the battery  

$$= 0.9 A_C \text{ ($/yr)/bus} \quad (B.2)$$

The high rate of charge employed gives rise to a life of only one year, at which time the scrap value is 10%.

- The annual capital cost of the storage and maintenance facility  

$$= 1.2 C_{30}M_C \text{ ($/yr)/bus} \quad (B.3)$$

- The annualized capital cost of the power distribution system  

$$= 1.2 C_{30}W_C \text{ ($/yr)/route-km} \quad (B.4)$$

- The maintenance cost of the power distribution system  

$$= K_C \text{ ($/yr)/route-km} \quad (B.5)$$

To obtain the total annualized cost of capital and annual maintenance, it is necessary to divide Equations B.4 and B.5 by N, the number of buses per-route km, before adding the result to Equations B.1, B.2, and B.3. Thus:

- Total of annualized capital and route maintenance cost  

$$= C_{15}B_C + C_{30}P_C + 0.9 A_C + 1.2 C_{30}M_C + (1.2 C_{30}W_C + K_C)/N \text{ ($/yr)/bus} \quad (B.6)$$

This cost can now be obtained in terms of the kilometres travelled by dividing Equation B.6 by the annual distance (D) travelled by the average bus. When this is done the other costs, which are closely related to distance travelled, can be added on to obtain the total life-cycle cost.

- Total life-cycle cost  

$$= O_C + T_C + I_C + (C_{15}B_C + C_{30}P_C + 0.9 A_C + 1.2 C_{30}M_C)/D + (1.2 C_{30}W_C + K_C)/ND \text{ ($/km)/bus} \quad (B.7)$$

Alternatively, it is possible to substitute for N from Equation 4.7, Section 4, to obtain:

- Total life-cycle cost
 
$$= O_C + T_C + I_C + (C_{15}B_C + C_{30}P_C + 0.9 A_C + 1.2 C_{30}M_C)/D \quad (B.8)$$

$$+ hS(1.2 C_{30}W_C + K_C)/D \text{ ($/km)/bus}$$

In order to simplify the equations and permit comparison between the different systems, rough cost estimates have been made and substituted for the symbols . These are listed below:

|                                                            |       |                       |
|------------------------------------------------------------|-------|-----------------------|
| • Capital cost of bus body                                 | $B_C$ | = 100 000 \$/bus      |
| • Capital cost of bus propulsion system                    | $P_C$ | = 120 000 \$/bus      |
| • Capital cost of battery                                  | $A_C$ | = 13 500 \$/bus       |
| • Capital cost of maintenance and storage facility         | $M_C$ | = 26 000 \$/bus       |
| • Capital cost of wayside equipment                        | $W_C$ | = 240 000 \$/route/km |
| • Annual Cost of maintaining wayside system                | $K_C$ | = 6 300 \$/yr         |
| • Annual distance travelled by bus                         | $D$   | = 64 000 km/yr        |
| • Operational cost of bus excluding maintenance and energy | $O_C$ | = 0.93 \$/km/bus      |
| • Cost of maintenance and service                          | $I_C$ | = 0.40 \$/km/bus      |
| • Cost of fuel or energy                                   | $T_C$ | = 0.106 \$/km/bus     |
| • Bus schedule speed                                       | $S$   | = 20.0 km/h           |

With these elements substituted in Equation B.8, the life-cycle cost becomes:

- Life-cycle cost =  $1.954 + 0.054 h \text{ ($/km)/bus}$  (B.9)

When Equation B.9 is normalized to the diesel bus life-cycle cost of 1.463 (\$/km/bus) it becomes:

- Normalized Trolley/Battery bus life-cycle cost =  $1.336 + 0.037h$  (B.10)

The cost of energy for the Trolley/Battery bus is 0.106 (\$/km)bus.  
When normalized, this becomes 0.073.

For headways shown below, the normalized life-cycle cost becomes:

| <u>h</u> | <u>LCC</u> |
|----------|------------|
| 4        | 1.48       |
| 10       | 1.705      |

References B.1 and B.2 give normalized life-cycle costs of 1.4 with no headway specified.

#### B.5/ References

- [B1] Dietrich, E.O., Sahm, K., "Operational Data and Running Experience in the City of Esslingen of the Duo Bus," Electric Vehicle Development Group 2nd International Conference, May 23-24, 1978.
- [B2] Gurley, A., "Towards a More Versatile Public Passenger Transport System Based on Experience with the Leyland/Bosch/Chloride bus at Runcorn, Cheshire," Electric Vehicle Development Group, 2nd International Conference, May 23-24, 1978.

GLOSSARY

|     |                                                          |                |
|-----|----------------------------------------------------------|----------------|
| A   | Capital cost of battery                                  | \$             |
| B   | Capital cost of bus body                                 | \$             |
| C   | Capital cost factor                                      | ratio          |
| D   | Annual distance travelled by bus                         | (km/yr)/bus    |
| E   | Electrical energy used per km                            | (kWh/km)/bus   |
| F   | Cost of fuel before tax                                  | \$/L           |
| h   | Minimum bus headway                                      | min            |
| I   | Cost of maintenance and service                          | (\$/km)/bus    |
| J   | Cost of electrical energy                                | \$/kWh         |
| K   | Annual cost of maintaining wayside system                | \$/route-km    |
| M   | Capital cost of maintenance and storage facility         | \$/bus         |
| N   | Number of buses per route km                             | buses/route-km |
| O   | Operational cost of bus excluding maintenance and energy | (\$/km)/bus    |
| P   | Capital cost of bus propulsion system                    | \$/bus         |
| Q   | Diesel fuel consumption                                  | (L/km)/bus     |
| S   | Bus schedule speed                                       | km/h           |
| T   | Cost of fuel or energy                                   | (\$/km)/bus    |
| W   | Capital cost of wayside equipment                        | \$/route-km    |
| LCC | Life-cycle cost                                          | (\$/km)bus     |

Subscripts

|    |                            |
|----|----------------------------|
| d  | Diesel bus system          |
| T  | Trolley bus system         |
| b  | Battery bus system         |
| c  | Trolley/battery bus system |
| 30 | 30-year life               |
| 15 | 15-year life               |
| 3  | 3-year life                |